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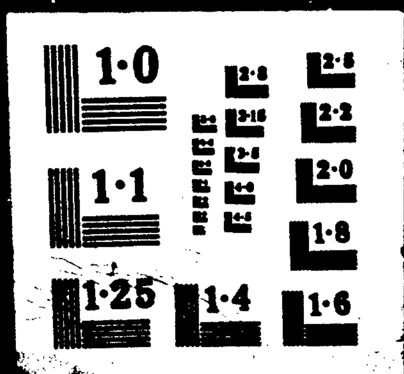

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[redacted] NAVORD REPORT 6750

THE DETONATION PROPERTIES OF DATB
(1, 3-DIAMINO, 2, 4, 6-TRINITROBENZENE (U)

QUALIFIED REQUESTERS MAY OBTAIN FROM DDC

12 OCTOBER 1960

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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THE DETONATION PROPERTIES OF DATB (1, 3-DIAMINO, 2, 4, 6-TRINITROBENZENE) (U)

By:

N. L. Coleburn, B. E. Drimmer, T. P. Liddiard, Jr.

Approved by: I. Kabik for A. D. SOLEM
Chief, Explosion Dynamics Division

ABSTRACT: The detonation parameters of the relatively new heat-resistant, shock-insensitive explosive DATB have been measured. At the normal, pressed-loaded density (1.80 g/cm^3), the detonation velocity is 7,600 m/sec, and the Chapman-Jouguet pressure is 251 kb. The detonation velocity (m/sec) varies with density (g/cm^3) according to $D = 2,480 + 2,852\rho$. The energy of detonation is 800 cal/g and 3.1 is the value of the isentropic exponent for product gas expansion. The failure diameter was found to be 0.53 cm. When mechanical shocks are slowly applied, as in the impact-hammer machine, DATB is less sensitive than TNT, but when the shock is more rapidly applied, as in the NOL wedge test, the explosive behaves more like Composition B. Addition of 5% plastic binder desensitizes DATB to rapidly-applied shocks, causing it to fail to build up to detonation in the wedge test even though the pressure within the explosive may be as high as 82 kb.

EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, SILVER SPRING, MARYLAND

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NAVORD Report 6750 12 October 1960

This study of the detonation properties of DATB is a phase in a broad program directed by the Explosions Research Department toward evaluation of new explosives of superior thermal stability. The work was authorized by Task No. RUUO 3E012/212 1/F008-10-004, Explosive Properties, formerly Task No. 301-664/43006/08, Explosives Applied Research, and is directly related to Explosives Research and Development Key Problem 7.3, "Initiation and Detonation", as given in NAVORD Report 3906.

The data herein reported are considered to be the best available at this date, but may not necessarily reflect the final opinion of this Laboratory.

W. D. COLEMAN
Captain, USN
Commander

E Swift

E. SWIFT, JR.
By direction

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THE DETONATION PROPERTIES OF DATB (1, 3-DIAMINO, 2, 4, 6-TRINITROBENZENE) (U)

Introduction

The speeds of modern aircraft, and especially those of unmanned missiles, have produced many difficult problems in ordnance design. The ability of the explosive component to tolerate severe thermal cycles experienced during the mission of such ordnance is an important parameter in these designs. A promising, new, shock-insensitive explosive, 1, 3-diamino, 2, 4, 6-trinitrobenzene (DATB)[1,2], has superior thermal stability under these conditions. DATB is a yellow solid having a crystal density of 1.837 g/cm^3; it melts at 286°C, and decomposes at a negligible rate at 204°C, while at 260°C its decomposition rate is only about 1% (by weight) per hour. It does not initiate at the maximum height (320 cm) of the NOL impact hammer machine, showing that DATB is much less sensitive to such slowly applied mechanical shocks than even TNT (200 cm). The detonation parameters of DATB and its sensitivity to rapidly applied shocks are reported herein.

Detonation Velocity of DATB and DATB-Plastic-Bonded Compositions

Detonation velocities as a function of charge density were measured for pure DATB and DATB/EPON 1001* (95/5) with a rotating-mirror smear camera. The velocities obtained from the photographic measurements (when the charge density was a maximum) checked to within 10 m/sec when camera and electronic pin probes were employed simultaneously. Simple pelleting techniques produced 5.0-cm diameter pellets for these tests, with densities ranging from 1.4 to 1.8 g/cm^3. To obtain charges with densities below 1.4 g/cm^3, the powder (average particle size 4 to 5 microns) was loaded in 15-gram increments into 5.1-cm internal diameter, 0.15-cm thick aluminum or glass tubes and pressed (in the aluminum tubes only) at pressures up to 8,000-10,000 psi. When the charges were confined by aluminum, the detonation wave was observed through a series of small, evenly-spaced holes drilled through the metal casing. Each test charge was initiated by an explosive train consisting of a U. S. Engineer's Special Detonator, a 5.1-cm diameter plane-wave generator (Baratol-Composition B), and a 5.1-cm diameter, 5.1-cm long tetryl pellet.

* Epoxy Resin; Shell Epon 1001; (Shell Chemical Company, Emeryville, California [redacted]

The detonation velocities are listed in Table I and plotted in Figure 1. At densities normally obtainable, 1.80 g/cm^3 (98.0% of crystal density), the detonation velocity of pure DATB is 7,600 m/sec. The detonation velocity varies linearly with the charge density according to the equation

$$D = 2{,}480 + 2{,}852\,\rho\ (\pm 25)\ \text{m/sec.} \qquad (1)$$

The diameter effect of pure DATB (density of 1.81 g/cm^3) was studied by detonating a pyramidal charge of three cylindrical pellets, 2.54-, 1.27- and 0.64-cm diameter, stacked in order of decreasing diameter. On top of the 0.64-cm diameter pellet was placed a 1.25-cm long truncated conical section tapering from 0.64-cm diameter at its base to 0.32-cm diameter at the top. Detonation of the pyramidal charge resulted in a normal velocity with detonation failure occurring at a charge diameter of 0.53 cm, i.e. within the tapered region.

Results obtained with DATB/EPON 1001 (95/5), Table II and Figure 1, show that at a given charge density this plastic-bonded explosive detonates about 150 m/sec slower than does pure DATB. A tapered section was not used in the DATB/EPON 1001 (95/5) pyramidal charge. Therefore the failure diameter of this composition was not ascertained. However, its ability to propagate stable detonation up to the end of a 2.54-cm long cylindrical pellet, 0.64-cm in diameter, demonstrated that its failure diameter is near to that of pure DATB.

The Chapman-Jouguet Pressure of DATB

Using a method reported by W. C. Holton[3], we have measured the Chapman-Jouguet pressure of DATB. This method involves the measurement of the velocity of the shock wave transmitted into water from the end of a plane-wave-initiated charge; then, employing an equation of state of water to obtain the pressure at the water-explosive interface, the Chapman-Jouguet pressure is inferred. In the experimental arrangement, Figure 2, a charge 15.2-cm long by 5.1-cm diameter, initiated by a Baratol-Composition B plane-wave generator, was immersed in distilled water to a depth of 6.4 cm. The bottom end of the charge was positioned parallel to, and 1.3 cm above, the optical axis of the smear camera. The shock wave within the water, "back-lighted" by collimated light from an exploding wire, produced a time-resolved shadowgraph, Figure 3. From measurements of this photographic trace the detonation pressure of the explosive is calculated using the water-shock wave data of Rice and Walsh[4]. Their data are represented by the following equation:

TABLE I

DETONATION VELOCITY OF DATB

Charge No.	Diameter (cm)	Length (cm)	Confinement	Density (g/cm^3)	Detonation Velocity (m/sec)
1*	Conical**	1.250	None	1.816	***
	0.64	2.540	"	1.816	7620
	1.27	2.644	"	1.815	7620
	2.54	7.861	"	1.809	7620
2	5.47	13.40	Glass	0.901	5050
3	5.47	15.31	Lucite	1.427	6600
4	4.48	15.53	" "	1.375	6470
5	4.44	15.26	Aluminum	1.381	6470
6	4.44	15.27	" "	1.285	6130
7	4.44	15.27	" "	1.205	5880
8	5.08	15.80	None	1.788	7570
9	5.08	20.47	"	1.793	7580

* Charge 1 was the pyramid charge in four sections.
** Diameter uniformly decreased from 0.64 to 0.32 over 1.25-cm length.
*** Failure diameter = 0.53 cm.

TABLE II

DETONATION VELOCITY OF DATB/EPON 1001 (95/5)

Charge No.	Diameter (cm)	Length (cm)	Density (g/cm^3)	Detonation Velocity (m/sec)
1*	0.638	2.545	1.776	7350
	0.953	2.545	1.765	7350
	1.267	2.436	1.756	--
	1.267	2.629	1.761	7280
	2.537	2.573	1.752	7400
	2.537	2.614	1.708	7180
2	5.053	15.00	1.733	7260
3	2.527	15.67	1.448	6480

* Charge 1 was a pyramid charge in six sections.

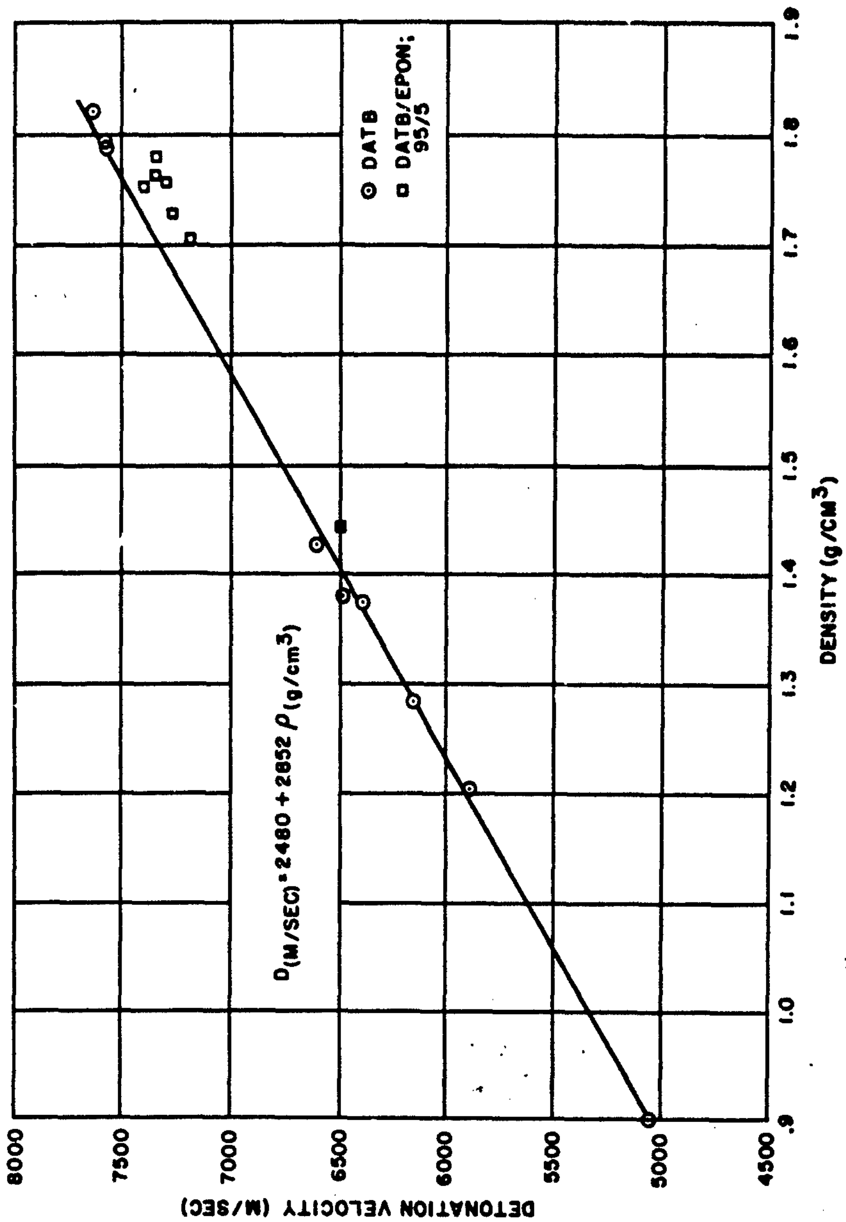

FIG. 1 DETONATION VELOCITY OF DATB AS A FUNCTION OF CHARGE DENSITY

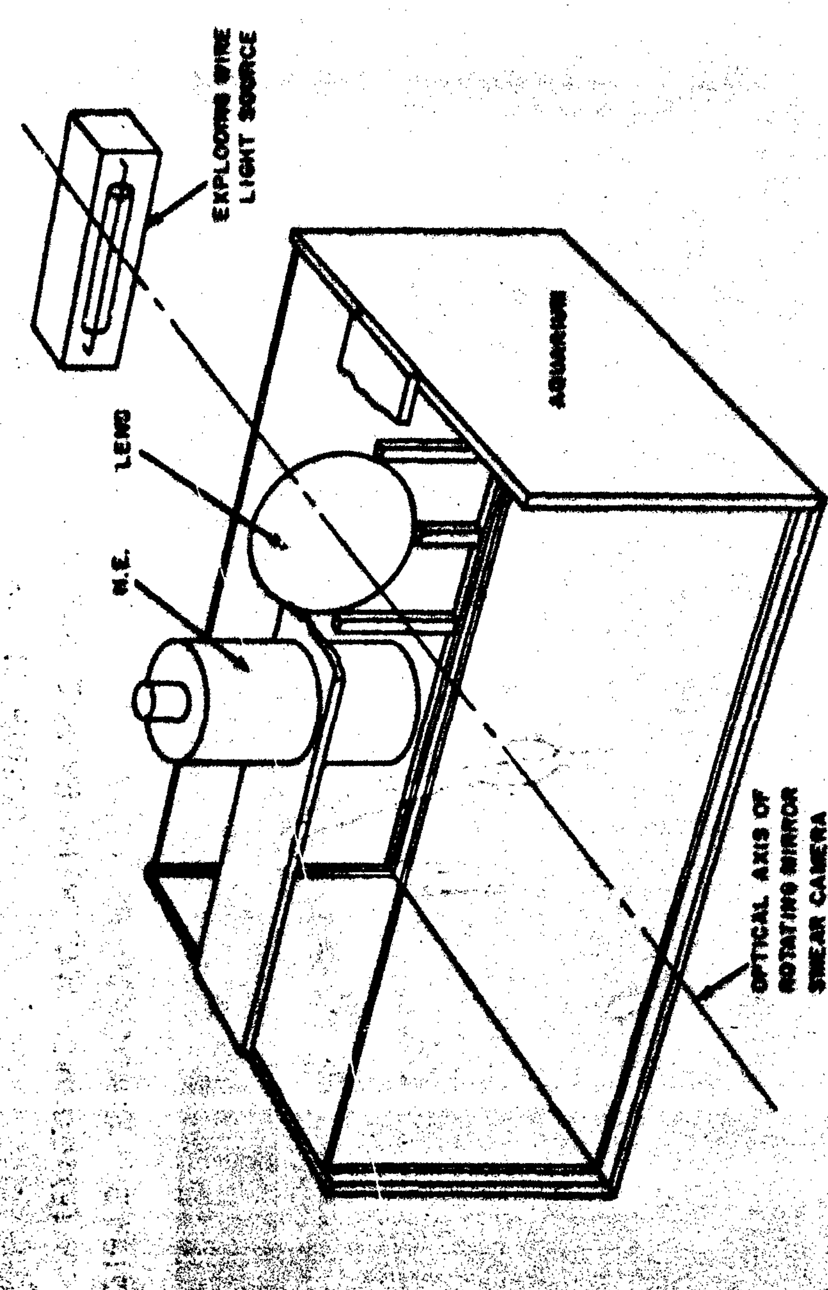

FIG. 2 ARRANGEMENT FOR MEASURING THE VELOCITY OF THE SHOCK WAVE TRANSMITTED INTO WATER AT THE END OF AN EXPLOSIVE CHARGE

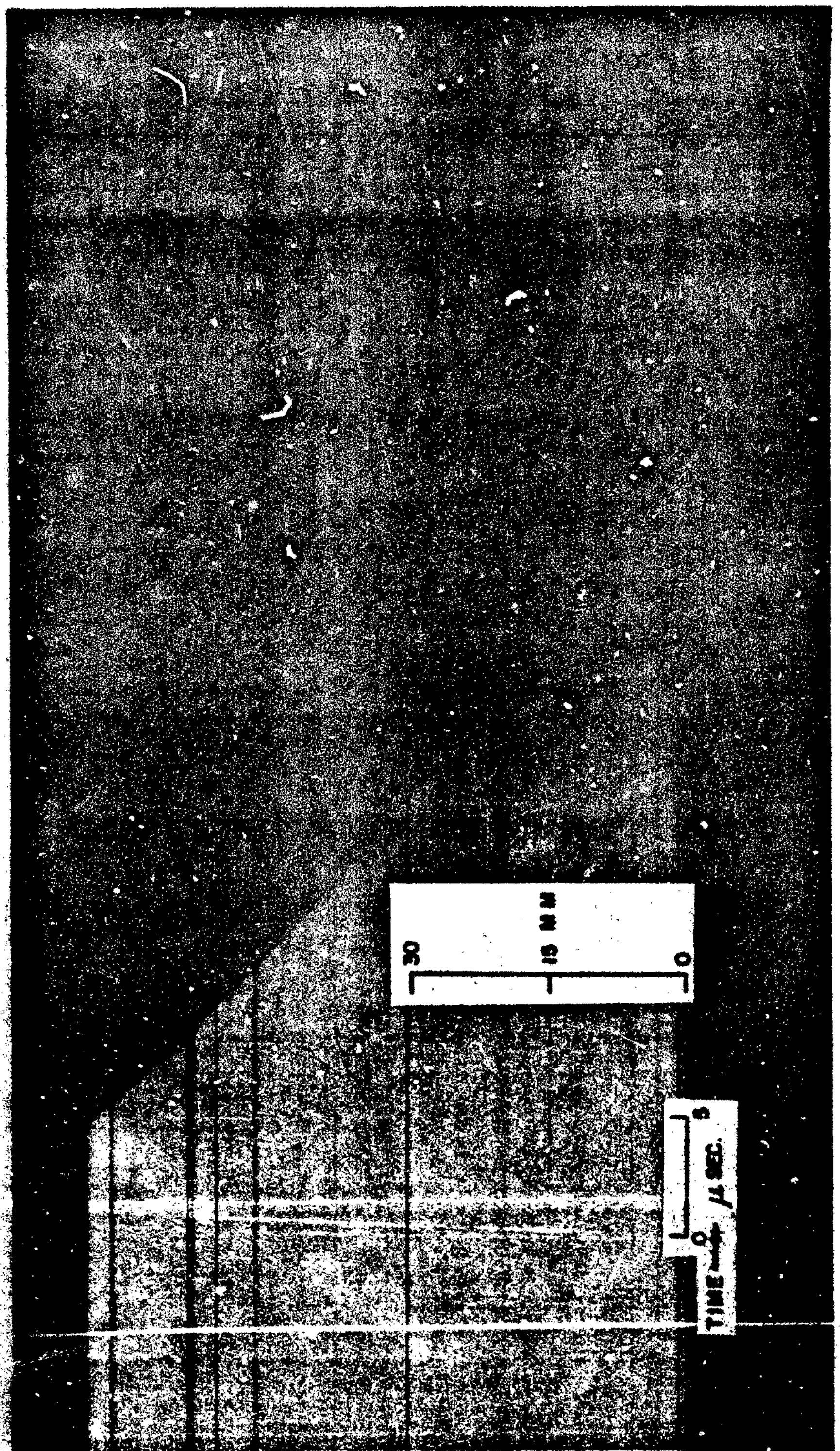

FIG. 3 SHADOWGRAPH OF WATER SHOCK PRODUCED BY DETONATION OF DATB (EXPLOSIVE - WATER INTERFACE WAS ALONG UPPER BOUNDARY OF LIGHTED REGION OF THE PHOTOGRAPH)

$$U - 1{,}483 = 25{,}306 \log_{10} (1 + u/5{,}190) \qquad (2)$$

where U is the shock velocity and u is the particle velocity of the water in m/sec. Thus a measurement of U at the explosive-water interface produces a corresponding value of u. The pressure, P, in the water at this interface is then obtained from the familiar hydrodynamic equation

$$P = Uu/V_o \qquad (3)$$

where V_o is the specific volume of material in the unshocked state.

A first estimate of P_1, the Chapman-Jouguet pressure of the explosive, is then obtained from the approximate relation[5]

$$P_1 \simeq P_{H_2O} \frac{(\rho_o U)_{H_2O} + (\rho_o D)_E}{2(\rho_o U)_{H_2O}} \qquad (4)$$

where P_{H_2O} is the pressure of the water at the explosive-water interface and $(\rho_o D)_E$ is the product of the initial density and detonation velocity of the explosive.

An improved measure of the Chapman-Jouguet pressure is made using the following analysis which is fully described in Appendix A. From the definition of the isentropic exponent,

$$k = -\left(\frac{\partial \ln P}{\partial \ln V}\right)_s , \qquad (5)$$

the Chapman-Jouguet condition,

$$\left(\frac{\partial P}{\partial V}\right) = - \frac{P_1}{V_o - V_1} , \qquad (6)$$

(the term P_o has been neglected here since $P_1 \gg P_o$) and the hydrodynamic relation

$$D^2 = V_o^2 P_1/(V_o - V_1) , \qquad (7)$$

one obtains

$$P_1 = \frac{1}{V_o} \frac{D^2}{(k+1)} . \qquad (8)$$

The quantities V_o and D are known; however, k is not known exactly and therefore P_1 cannot be computed with precision. A second relationship for P_1 that also involves k and other known quantities, derived from application of the Riemann postulate for an isentropic expansion of the detonation products from P_1 to the initial pressure transmitted into the water, is

$$P_1 = P_{H_2O}\left[1 - \frac{(k^2-1)u_{H_2O} - (k-1)D}{2kD}\right]^{-\frac{2k}{k-1}}. \tag{9}$$

Equations (8) and (9) are solved for P_1 and k by iteration using first, the approximate value of P_1 given by (4).

The DATB charges were fired each at an initial density of 1.790 ± 0.001 g/cm^3, yielding the following mean values:

$$D = 7{,}585 \text{ m/sec}$$

$$U = 5{,}980\ (\pm 28) \text{ m/sec}$$

$$u = 2{,}624 \text{ m/sec}$$

$$P_{H_2O} = 157 \text{ kb.}$$

From these data the isentropic exponent, k, is computed to be 3.10 and the Chapman-Jouguet pressure is 251 kb. This pressure is 33% greater than that of TNT(189 kb)[6] and only 13% less than that of 65/35 RDX/TNT(290 kb).[7]

The Energy of Detonation

The energy of detonation can be estimated from the assumption that on detonation the oxygen in the explosive forms $H_2O_{(g)}$, $CO_{(g)}$, and $CO_{2(g)}$ in that order. For DATB this reaction is

$$C_6H_5N_5O_6 \longrightarrow \tag{10}$$

$$2.5\ H_2O_{(g)} + 3.5\ CO_{(g)} + 2.5\ N_{2(g)} + 2.5\ C_{(c)}$$

The measured heat of formation of DATB is 29.23 kcal/mole.[8] Using available heat-of-formation data for the decomposition products, the heat of detonation is calculated to be 875 cal/g.

The heat of detonation also can be calculated from the experimentally determined values of the detonation velocity, the detonation pressure, and isentropic exponent. Thus, as shown by Jacobs[9] and Price[10], the energy of detonation is

$$Q = \frac{D^2}{2(k^2 - 1)} \qquad (11)$$

From this relation it is calculated that Q is 800 cal/g, differing by 8.7% from the energy calculated from thermal data. For convenience the detonation parameters are assembled in Table III where they are compared to corresponding values for TNT.

Sensitivity to Rapidly-Applied Shocks

Evaluation studies were performed on pure DATB, DATB/EPON 1001 (95/5), and DATB/BRL 2741* (95/5) using the NOL wedge test[11]. In this test, Figure 4, the explosive, formed into a 25-degree wedge with a maximum thickness of 1.27 cm, is subjected to a plane shock wave delivered by an explosively-driven brass plate. Plates of 1.27-, 2.34-, and 3.81-cm thicknesses are used in order to vary the shock pressure transmitted into the explosive. The shock wave within the metal is formed by the detonation of a 1.27-cm thick Composition B slab, 12.7 cm square, initiated by a 10.8-cm diameter plane-wave generator. The shock velocity within the unreacted explosive, as a function of explosive thickness, and the build-up to the steady detonation velocity, are inferred from an analysis of the smear-camera photograph of the shock arrival at the free surface of the wedge (Figure 5, central region). Reflected-light technique is used to record the shock arrival and to measure the shock-wave parameters of the brass plate.

The results obtained for the build-up-to-detonation tests on DATB using the three brass thicknesses are shown in Figures 6-8, where they are compared to those obtained for Composition B. The outstanding feature of these curves is the fact that the instantaneous shock velocity within the explosive rises 10-20% above the normal detonation velocity before settling down to that value. An example of this velocity "overshoot" can be seen in the smear-camera photograph for Shot 1 (Figure 5). In this respect DATB behaves like other pressed explosives. No cast explosive has exhibited such an "overshoot", while pressed explosives characteristically do[12].

---

* Phenolic resin (Bakelite Corporation, New York City, New York).

TABLE III

PROPERTIES OF DATB COMPARED TO TNT

Property	DATB	TNT
Experimental Density (g/cm^3)	1.800	1.637
Detonation Velocity (m/sec)	7,600	6,940
$\frac{dD}{d\rho_o}$ $\frac{(m/sec)}{(g/cm^3)}$	2,852	3,225
Failure Diameter (cm)	0.53	1.3 [14]
Detonation Pressure (kb)	251	189 [6]
Detonation Energy (cal/g)	800	636
50% Impact Initiation Height (cm)	$>$320	200
Isentropic Exponent, k	3.1	3.17
Plate-Push Value, (ft/sec)	3,130	2,930

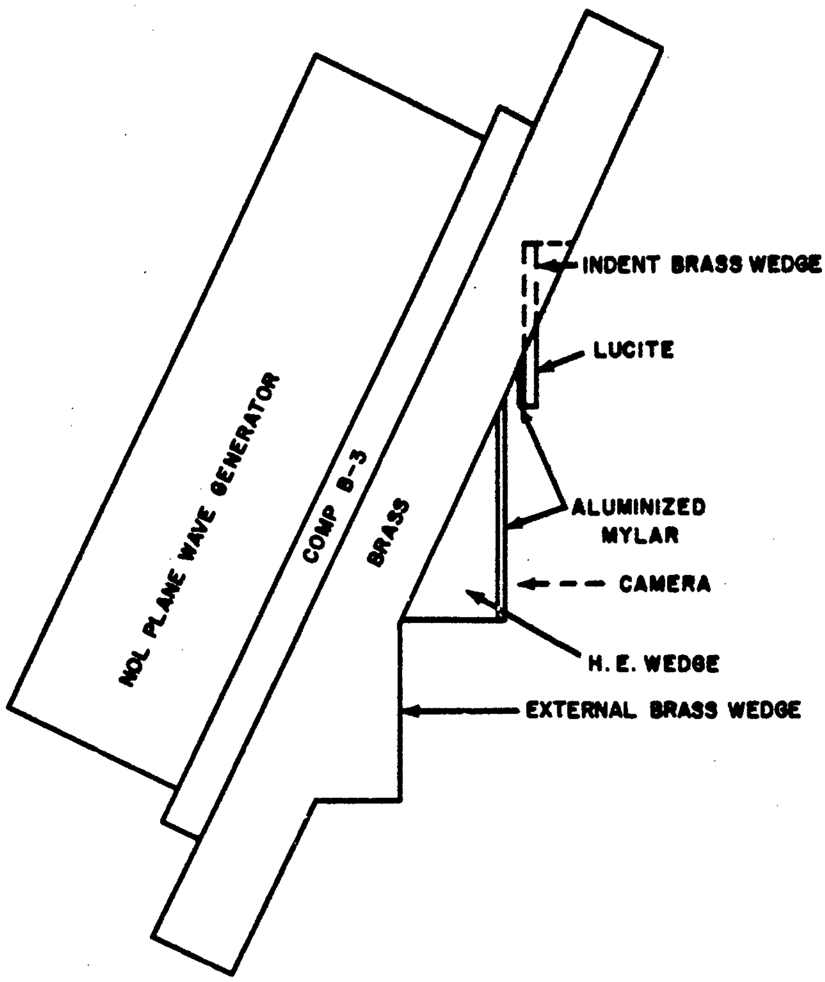

FIG. 4 SIDE VIEW OF NOL WEDGE-TEST ARRANGEMENT

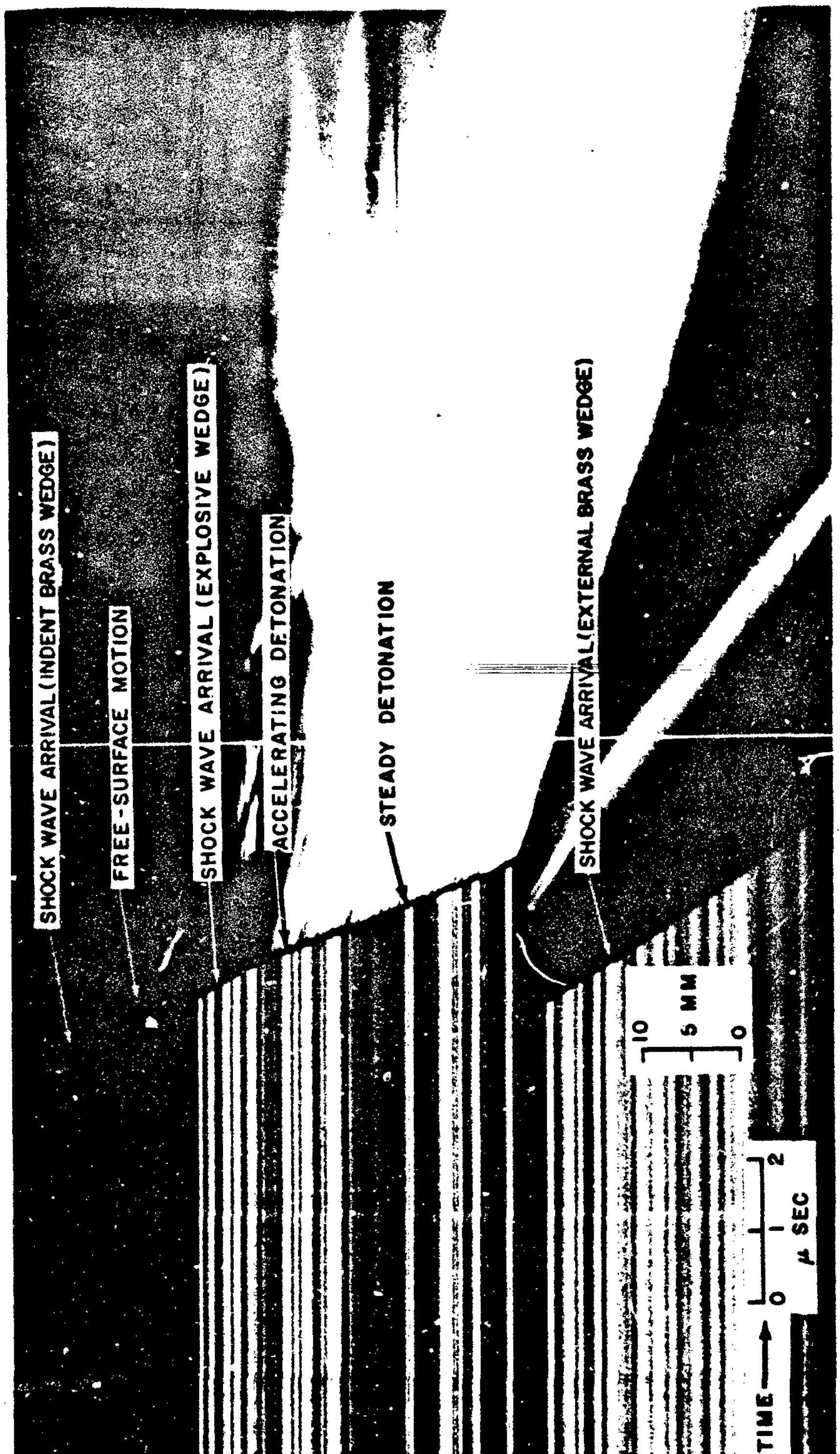

FIG.5 SMEAR CAMERA RECORD OF THE DETONATION OF DATB IN THE NOL WEDGE TEST USING 1.27 CM-THICK BRASS

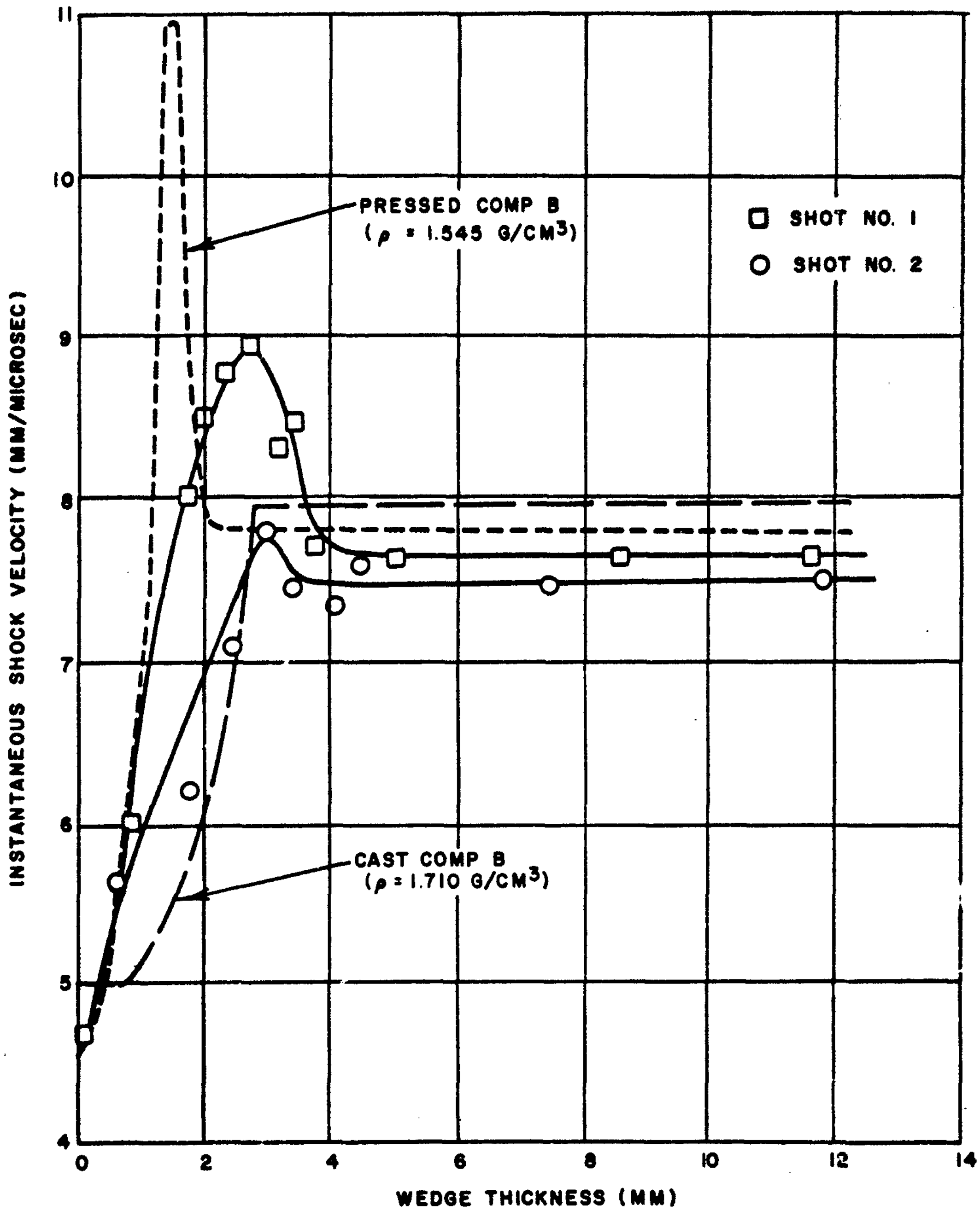

FIG. 6 INSTANTANEOUS SHOCK VELOCITIES IN DATB FOR 1.27-CM THICK BRASS COMPARED WITH COMP B

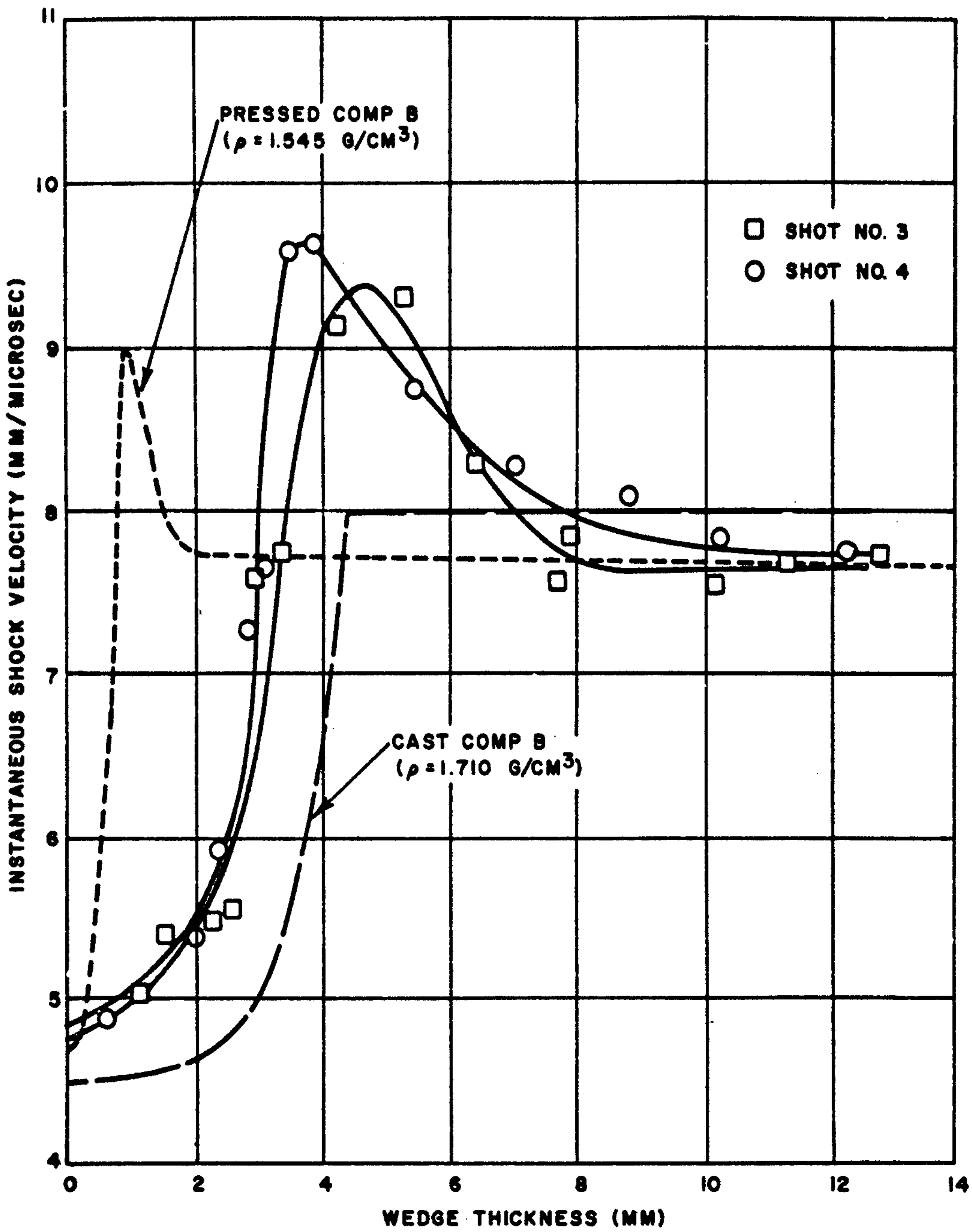

FIG. 7 INSTANTANEOUS SHOCK VELOCITIES IN DATB FOR 2.54-CM THICK BRASS COMPARED WITH COMP B

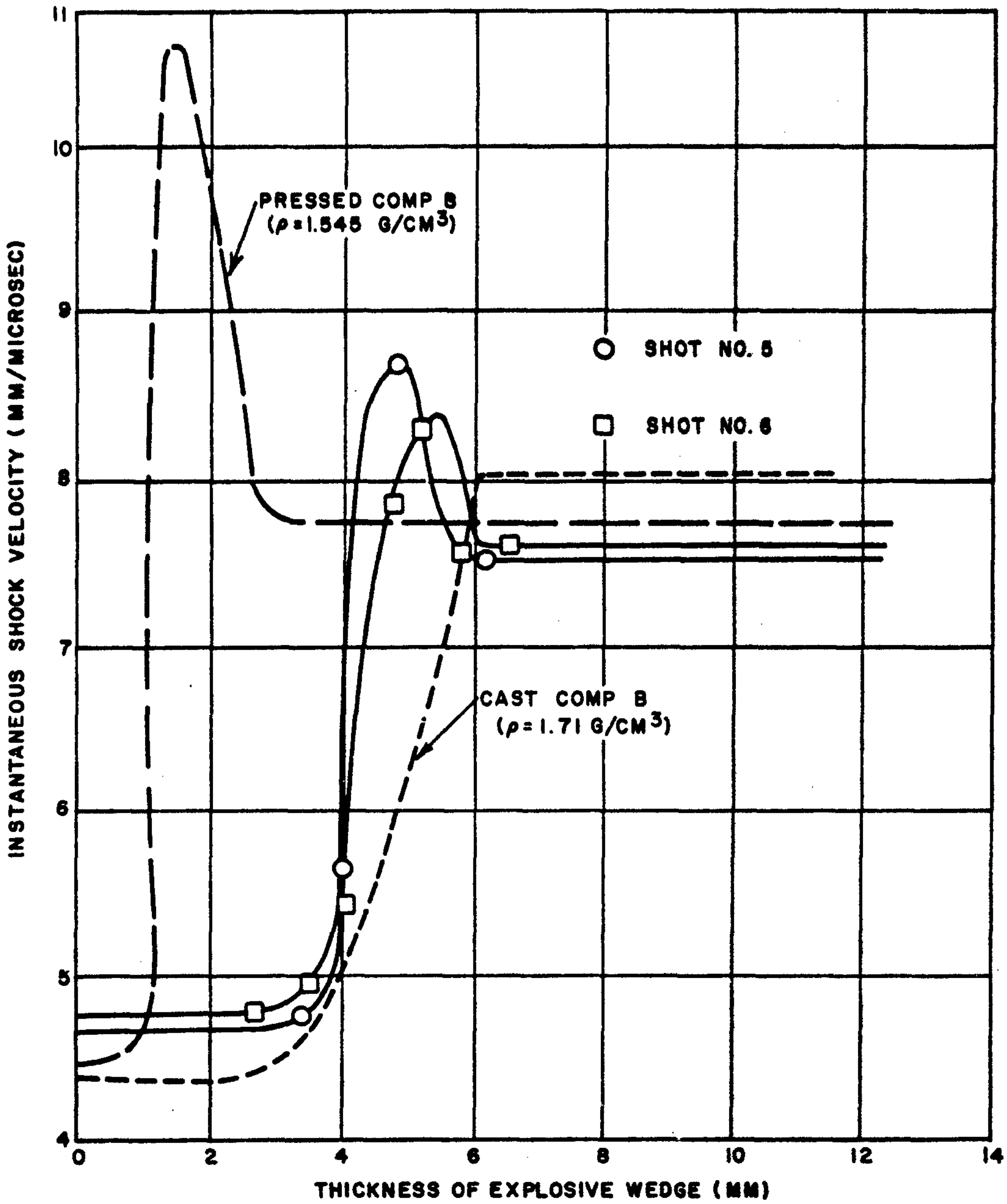

FIG. 8 INSTANTANEOUS SHOCK VELOCITIES IN DATB FOR 3.81-CM THICK BRASS COMPARED TO COMP B

Another feature shown in Figures 4-6 is that the build-up-to-detonation of DATB under this rapid shock-loading is not significantly different (other than the "overshoot") from that of cast Composition B[11]. Thus the sensitivity of DATB to mechanical shocks is strongly dependent on the rate of shock-loading; when applied slowly, as in the impact-hammer machine, DATB is very insensitive (the 50% initiation point exceeds 320 cm, while for TNT it is 200 cm and for Composition B it is 60 cm)[13]. When the shock is applied rapidly, as in the wedge test, the sensitivity of DATB is comparable to that of cast Composition B (TNT fails completely to build-up to normal detonation velocity in the wedge test[11]).

The NOL wedge test was designed to permit for each shot a determination of one point on the Hugoniot curve for the unreacted explosive. Analysis of the upper region of Figure 3 yields the free-surface velocity and the shock velocity of the brass at its free surface, and thus, by equation (3), the pressure in the brass at the brass, explosive-wedge interface (assuming that the particle velocity of the brass is one half its free-surface velocity). An equation analogous to equation (4) then produces the pressure within the unreacted explosive at the same interface. If its compression, V/V_o (where V_o and V are respectively, the specific volume of the explosive before and after being shocked), is calculated for the same state, then the point on the Hugoniot curve will have been determined. The compression is calculated from the continuity equation for the explosive

$$\frac{V}{V_o} = \frac{U - u}{U} \qquad (12)$$

using equation (3) to obtain the particle velocity, u, of the unreacted explosive. In this manner three points on the Hugoniot curve for the unreacted explosive have been determined for pressures of approximately 75, 85, and 100 kb. The exact values, as well as the other parameters derived from the wedge test are tabulated in Table IV and Table V.

A few explanatory remarks on the data in Table IV are appropriate. The final, or steady value of the instantaneous velocity, D, should be identical with the normal detonation velocity. The observed deviations from this value are merely the result of the difficulties of making a precision velocity measurement by this method. The smallest tilt, or non-planarity of the wave as it emerges from the explosive wedge would alter the value of D. Thus the measurement of D, while not good enough for a determination of a precise detonation velocity, serves as a useful measure of the normal, plane-wave propagation assumption of the wedge test.

TABLE IV

WEDGE-TEST PARAMETERS FOR PURE DATB

Shot No.	Brass thick (cm)	Shock velocity -brass- (m/sec)	Particle velocity -brass- (m/sec)	Shock velocity -H.E.- (m/sec)	Particle velocity -H.E.- (m/sec)	Shock pressure -H.E.- (kb)	Relative volume -H.E.- (V/V_o)	H.E. density (g/cm^3)	D (m/sec)	Delay time (microsec)
1	1.27	4630	710	4670	1167	99.2	.750	1.820	7640	.07
2	1.27	4630	710	4660	1167	99.3	.750	1.825	7460	.16
3	2.54	4460	600	4870	972	85.4	.800	1.803	7620	.24
4	2.54	4460	600	4700	979	82.8	.792	1.799	7700	.20
5	3.81	4380	550	4736	892	76.6	.810	1.813	7590	.29
6	3.81	4380	550	4767	892	76.5	.815	1.810	7500	.26

TABLE V

WEDGE-TEST PARAMETERS FOR PLASTIC-BONDED COMPOSITIONS OF DATB

Shot No.	Brass thick (cm)	Shock velocity brass (m/sec)	Particle velocity brass (m/sec)	Shock velocity H.E. (m/sec)	Particle velocity H.E. (m/sec)	Shock pressure H.E. (kb)	Relative volume H.E. (V/V_o)	H.E. density (g/cm^3)	D (m/sec)	Delay time (microsec)
DATB/BRL 2741 (95/5)										
1	1.27	4,630	710	4,820	1,164	99.4	.759	1.77	7,350	.17
2	2.54	4,460	600	4,720	982	82.0	.792	1.77	Failed to Detonate	
DATB/EPON (95/5)										
1	2.54	4,460	600	5,120	971	86.0	.810	1.73	7,350	.17

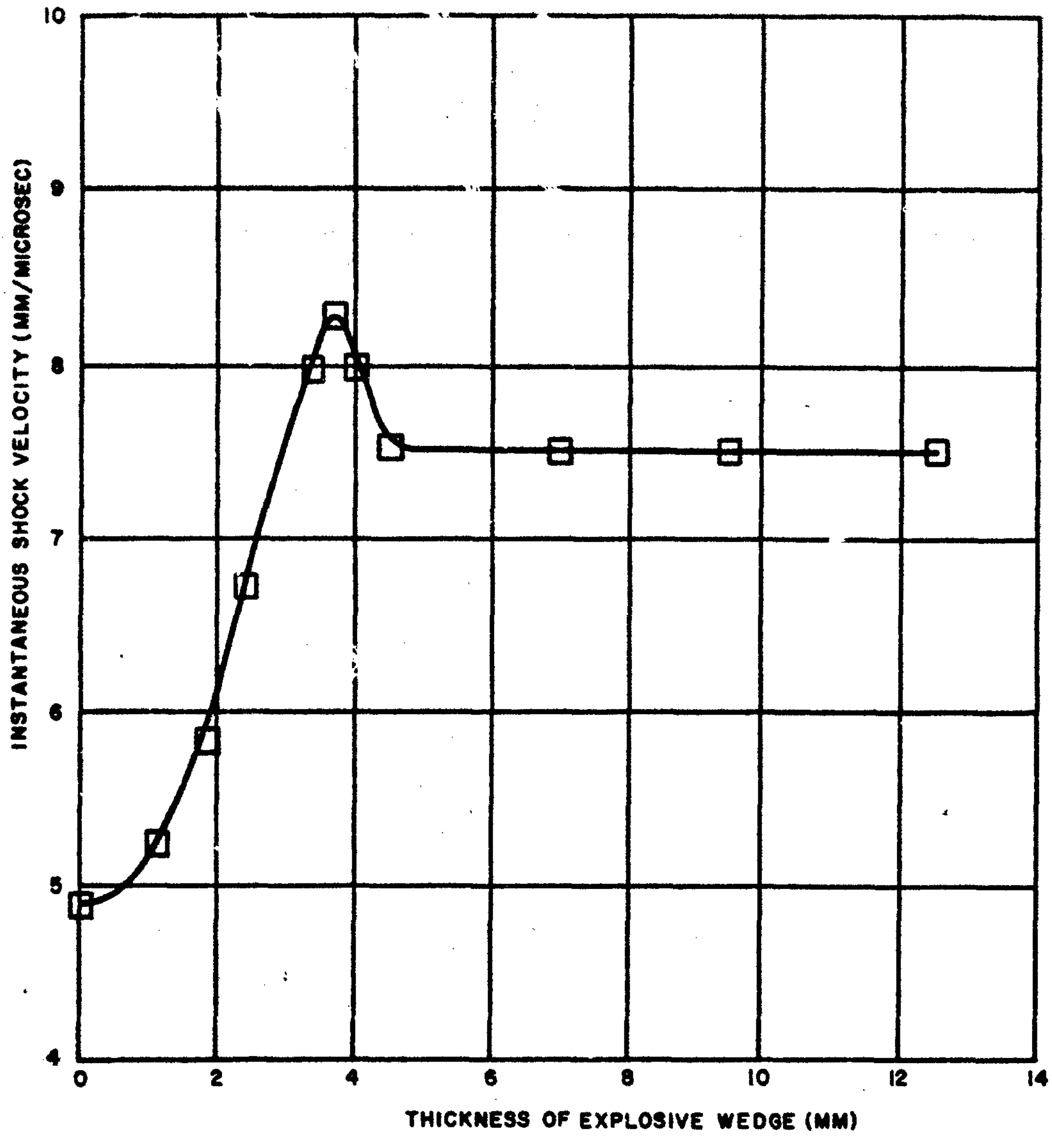

FIG. 9 INSTANTANEOUS SHOCK VELOCITIES IN DATB/BRL 2741 (95/5), FOR 1.27-CM THICK BRASS

The fact that the shock within the explosive wedge does not move always at its normal detonation velocity means that the shock (or detonation) wave is "delayed" in reaching a given depth in the explosive. The "delay time" is defined as the difference in time of arrival of the wave within the explosive between its actual time of arrival and the time it would have arrived had it moved always at its steady detonation velocity:

$$\text{Delay time} = (\text{time-of-arrival})_{\text{"observed"}} - (\text{time-of-arrival})_{\text{"steady shock"}}. \qquad (13)$$

(Of course, these times of arrival are calculated for some point beyond that where the steady velocity has been attained). The fact that velocity "overshoots" occur, produces the possibility that negative "delays" could be obtained, i.e., the shock could arrive even before it would have, had it travelled at its steady velocity at all times. Thus Shot 1 (with a 1.27-cm thick brass plate) exhibits a delay time of only 0.07 microsec as contrasted with 0.20-0.30 microsec for the other five shots.

Wedge tests also were run for plastic-bonded DATB/BRL 2741 (95/5) and DATB/EPON 1001 (95/5). With DATB/BRL 2741 (95/5), build-up to detonation (Figure 9) was obtained with a wedge shocked by 1.27-cm thick brass. But when 2.54-cm thick brass was used, the plastic-bonded explosive failed to build-up to detonation, even though the pressure developed within the explosive was 82 kb. Build-up to detonation was obtained with DATB/EPON 1001 (95/5) in the 2.54-cm thick brass plate wedge test.

Plate-Push Tests

The NOL plate-push test measures the ability of a 5.4-cm diameter by 6.3-cm long cylinder of explosive to project a 5.4-cm diameter steel disc (200 g) from a small expendable 1.25-cm thick steel mortar. The velocity imparted to the disc, in ft/sec, is the "plate-push" value of the explosive. Pure DATB gives a value of 3130 ft/sec and is thus intermediate to TNT (2930) and Composition B (3320).

Conclusions

1. At normal densities (1.78-1.80 g/cm^3) the detonation velocity of DATB is about 7600 m/sec, or more exactly, its velocity is represented by

$$D = 2480 + 2852\rho \text{ (m/sec)}.$$

At a density equal to the crystal density of TNT (1.654 g/cm^3), charges of DATB have a detonation velocity of 7200 m/sec, or 200 m/sec greater than that of TNT of the same density.

2. The sensitivity of DATB to rapidly applied, large-amplitude shocks (as in the wedge test) is comparable to that of cast Composition B. This contrasts strongly to its behavior under slowly applied, low-amplitude shocks (as in the drop-hammer impact test), where it is much less sensitive than even TNT.

3. The shock sensitivity of DATB is markedly reduced even for rapidly applied, large-amplitude shocks by the addition of only 5% of certain plastic binders.

4. In the wedge test (and presumably for mechanical impacts of a similar nature) the velocity of the shock wave passing through DATB starts at 4500-5000 m/sec and accelerates to a value exceeding the normal detonation velocity before finally settling back to normal detonation velocity. In this regard, DATB behaves similarly to other pressed explosives, which also exhibit this velocity "overshoot".

5. The small failure diameter of DATB, 0.53 cm, appears surprising ~~at first~~ glance. Its very large impact-hammer 50% height would lead one to expect a much larger failure diameter, say something comparable to the 1.3-cm diameter found for TNT[14]. However, our wedge tests indicate that for high pressure, rapidly applied shocks (such as it might also receive from its own detonation) the sensitivity of DATB is comparable to that of Composition B. The small failure diameter lends further support to conclusion 2 above, since the failure diameter of Composition B is approximately 0.4 cm[15].

6. Using water as a calibrated manometer, the measured Chapman-Jouguet pressure of DATB was found to be 251 kb, thus exceeding that of TNT by about 33% (considering each explosive at its normally obtainable charge density).

7. The isentropic exponent, k, of the product gases at the detonation front is calculated to be 3.10.

8. With this value of k, the energy of detonation of DATB is calculated from equation (11) to be 800 cal/g, or some 9% less than the value of 875 cal/g obtained from its measured heat of formation.

9. The plate-push value for DATB is 3130 ft/sec, about 6% higher than that of TNT.

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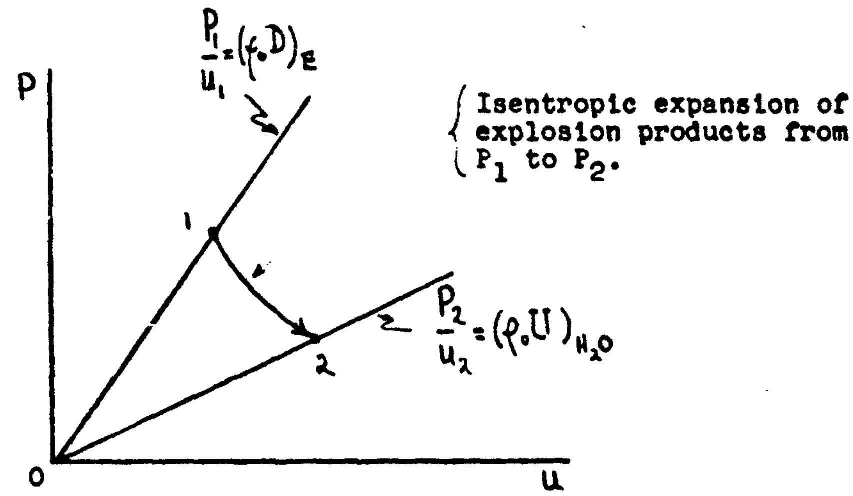
APPENDIX A (U)

Determination of the Chapman-Jouguet Pressure and the Isentropic Exponent of Detonation Products from Transmitted Shocks

The Chapman-Jouguet pressure of an explosive can be determined from measurements made on the shock wave its detonation transmits into material placed at the end of the charge. This method requires an accurate calibration of the equation of state of this inert material: water is one of the most convenient of such materials, its equation of state having been the subject of intensive study in recent years. We have chosen the data of Walsh and Rice for this purpose.

In this method a cylindrical explosive charge is immersed in water, its upper end protruding above the surface. Initiated by a plane-wave generator, the detonation wave strikes the water at normal incidence, and the resulting shock in the water is recorded (by back-lighting) using a rotating-mirror smear camera. A careful analysis of the resulting photograph yields the shock velocity within the water, at the original water-explosive interface, at the instant the shock crosses this interface. The published equation of state then produces from this number, the pressure and particle velocity of the water at the same point. From these values the Chapman-Jouguet pressure of the explosive and the isentropic exponent of its detonation products can be calculated by means of the equations about to be derived.

It is assumed that the usual conservation equations apply across the interface, and that all processes are performed adiabatically. After the detonation wave arrives at the explosive-inert interface a shock is transmitted into the inert material and a shock or a rarefaction (depending on shock impedance conditions) is reflected back into the explosive products. Between these two shock fronts (one of which might be a rarefaction, as just stated) it is assumed that the pressures and the particle velocities in both media are equal. In the following analysis a square-step shock across the interface is assumed. By considering the conditions at the interface at the time when the shock has barely penetrated into the inert material, i.e. at the extrapolated point where the thickness of the inert material vanishes, the errors introduced by this assumption are considered to be negligible.



Pressure-velocity diagram.

If u_1 is the particle velocity of the product gases at the C-J plane of a one-dimensional detonation wave, then the particle velocity u_2 of the product gases can be obtained from the Riemann relation

$$u_2 - u_1 = -\int_{\rho_1}^{\rho_2} \frac{c}{\rho}\, d\rho \; . \tag{14}$$

Thus a solution of this integral will give a value for u_2, which by the continuity assumption is also the particle velocity in the shocked water. Conversely, then, if u_2 can be determined by independent means, u_1 can be calculated, permitting a determination of the C-J pressure. An expression will now be derived for the right hand side of equation (14) which by further manipulation will provide an equation for the C-J pressure of the explosive in terms of the particle velocity and pressure of the water at the interface. This equation contains another unknown, k, the isentropic exponent for the product gases. Solution of this equation is then obtained by the simultaneous use of another equation containing k, the C-J pressure, and the (known, or independently measured) detonation velocity.

The velocity of sound, c, in the product gases is defined by the relation

$$c^2 = v^2\left(-\frac{\partial P}{\partial v}\right)_S = \left(\frac{\partial P}{\partial \rho}\right)_S \; ; \tag{15}$$

and thus at the detonation front

$$c_1^2 = v_1^2\left(-\frac{\partial P}{\partial v}\right)_S . \tag{16}$$

Again for the product gases,

$$\left(\frac{\partial P}{\partial v}\right)_S = -\frac{P_1}{V_0 - V_1} ,$$

so that

$$\frac{c_1^2}{V_1^2} = \frac{P_1}{V_0 - V_1} \; ; \tag{17}$$

and since

$$D^2 = \frac{V_0^2 P_1}{V_0 - V_1} ,$$

one obtains

$$D = \frac{V_0}{V_1} c_1 = \frac{\rho_1}{\rho_0} c_1 . \tag{18}$$

From the isentropic equation of state for the product gases

$$Pv^k = A \tag{19}$$

one obtains from its definition,

$$c_1^2 = kP_1V_1 = \frac{kP_1}{\rho_1} \tag{20}$$

or

$$c_1^2 = Ak\rho_1^{k-1} , \tag{21}$$

where A and k are constants.

Since

$$P_1 = D u_1 \rho_0 , \tag{22}$$

substitution of equation (18) for D, and combining the result with equation (20) one gets

$$k = \frac{c_1}{u_1} . \tag{23}$$

From the Chapman-Jouguet assumption,

$$D = u_1 + c_1 \tag{24}$$

we therefore have

$$u_1 = D/(k+1) \tag{25}$$

and

$$c_1 = kD/(k+1) . \tag{26}$$

Equation (21) permits a substitution of C_1 into the right-hand member of equation (14), making possible its integration, with the result

$$u_2 - u_1 = \frac{2c_1}{k-1}\left(1 - \frac{c_2}{c_1}\right), \tag{27}$$

where, it is recalled, subscript 2 refers to the state within the product gases behind the C-J plane. Simple substitutions for u_1 and the sound velocities now produce the desired relation for the C-J pressure. From equation (21)

$$\frac{c_2}{c_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\frac{k-1}{2}} , \tag{28}$$

and the isentropic law

$$\frac{\rho_2}{\rho_1} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{k}} , \tag{29}$$

it follows that

$$\frac{c_2}{c_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{2k}} \tag{30}$$

and thus

$$u_2 - u_1 = \frac{2c_1}{k-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{2k}}\right] . \tag{31}$$

Substituting for u_1 and C_1 their values in equations (25) and (26), one gets finally for the Chapman-Jouguet pressure,

$$P_1 = P_{H_2O}\left[1 - \frac{(k^2-1)u_{H_2O} - (k-1)D}{2kD}\right]^{\frac{-2k}{k-1}} . \qquad (32)$$

(P_{H_2O} and u_{H_2O} have been substituted for P_2 and u_2 by working our assumption of continuity of pressure and particle velocity across the interface).

A second equation in P_1 and k is needed to solve equation (32). This is obtained by substituting the value of u_1 from equation (25) into equation (22), yielding the relation

$$P_1 = \frac{\rho_o D^2}{k+1} . \qquad (33)$$

No simple, explicit solution is obtained for P_1 and k, and the solution is therefore obtained by iteration. This process is speeded by use of equation (4),

$$P_1 \approx P_{H_2O} \frac{(\rho_o U)_{H_2O} + (\rho_o D)_E}{2(\rho_o U)_{H_2O}} ,$$

to produce a close, first estimate for P_1 which then is applied to equation (33), etc.

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